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GROUND VIBRATION DUE TO BLASTING AND ITS EFFECT UPON STRUCTURES

BY F. J. CRANDELL, Member*

INTRODUCTION

BUILDING vibrations and the determination as to whether these vibrations cause damage to the structures has been for some time a controversial subject.

As far as earthquake vibrations are concerned, there still is a difference of engineering opinion regarding the design of structure to withstand them.

Certain phases of the construction industry, by their very nature, produce earth vibrations that are imposed upon structures and buildings. One of the most common operations of this nature is the use of explosives which assist in the excavation for foundations, tunnels, sewers, etc.

When the property owners feel the vibration and hear the detonation of the explosives, they immediately question, "Will the ground movement injure my building?" By this same token, when a contractor sets up his procedure for the use of explosives, he is likely to think, "How many pounds can I use without injury to structures? Will I have to reduce the number of pounds because of the nearness of these structures?"

This research was instigated in order to establish information that will assist the contractor in determining a safe charge of explosives to use in his excavation procedure and to insure no damage to adjacent structures.

Other organizations have investigated building vibrations and produced very informative data. However, most all the building vibration determinations have been made in the structure itself. Forced vibrations have been imposed upon the buildings and structures to determine their natural frequency. Measurements have been made upon the slabs and walls of structures to determine how much vibration they could withstand, and certain threshold determinations have been established.

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When a contractor is confronted with 500 to 1,000 buildings adjacent to his operation, a situation that occurs in a long tunnel job, it is not practical to measure the vibration within each structure itself.

If the intensity of ground vibrations could be used as the indicator of structural damage, it would not be necessary to measure the vibration in each individual structure.

Therefore it became our objective to try and determine the amount of ground vibration that would be needed before injuring the structure, and a method of predetermining the amount of charge of dynamite that could be used safely without damaging or rupturing any part of the structure.

With this in mind we investigated the ground vibrations produced by the use of explosives.

INSTRUMENT

In 1936, it was decided to design an instrument that would assist in measuring vibrations that exist in the ground during construction operations.

Because we were interested in measuring the magnitude and direction of forces transmitted through the ground, our present recording accelerometer (or accelerogaph) was designed to measure the accelerations in three planes.

Figure 1 shows the three reeds in the vertical, transverse, and longitudinal planes which are activated when vibration occurs. To these three reeds are attached mirrors which pick up a light source in the box and transmit the light beam on to a 35 mm. motion picture film.

The natural frequencies of the vibrating reeds are between 90 and 100 cycles per second. As a rule, the elastic frequencies in the earth and rock have been below the natural frequency of these reeds.

The 35 mm. film travels at a speed of 3¾ inches per second.

It will be noted in Figure 1 that there are dampening pots containing stiff grease attached to each reed to give a fairly sharp dampening after the external vibration ceases.

With this accelerograph we have measured vibrations produced by dynamite in the course of blasting rock and earth, tremors produced by the driving of piles, and vibrations produced by machine rotation in the flooring system of manufacturing buildings.

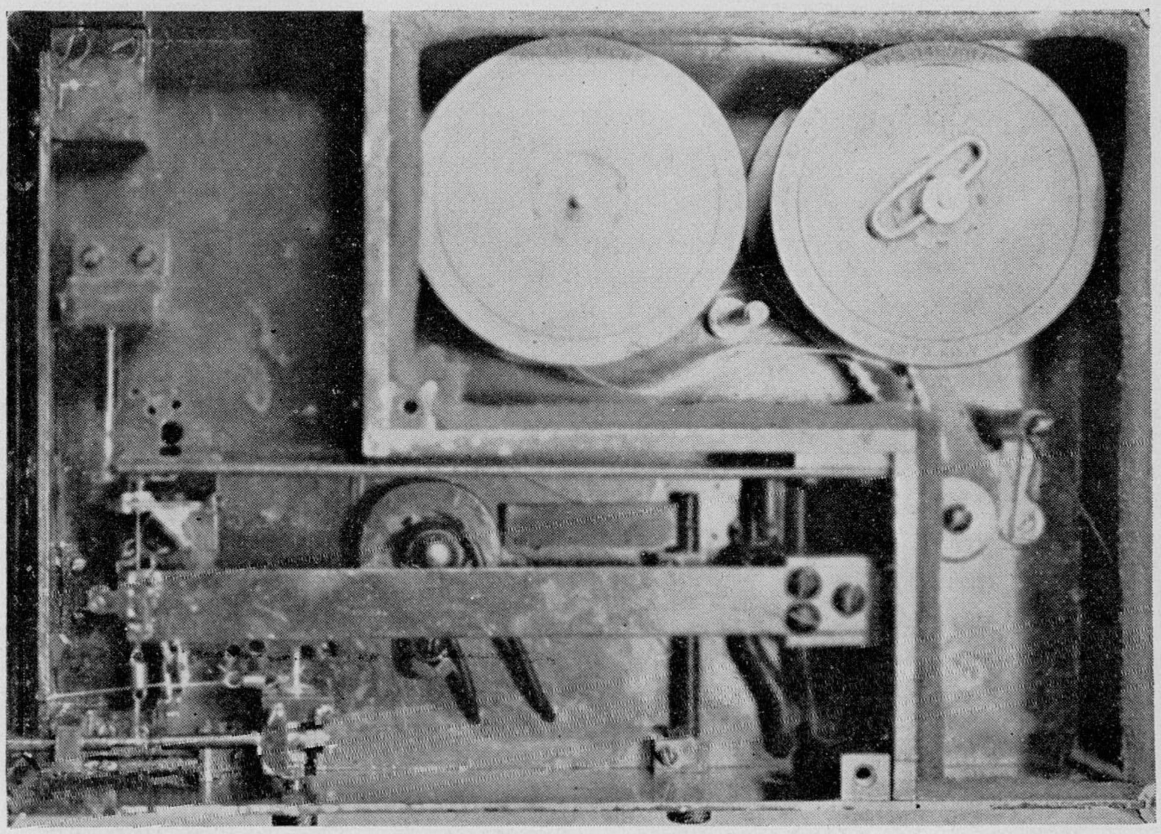


FIG. 1.—ACCELEROGRAPH.

This study is primarily concerned with vibrations due to blasting that are relatively close to the source of energy that produces them. Most of our measurements were taken at a distance of from 20 to 200 feet from the energy source.

CONCLUSIONS

1. This investigation indicates that Energy Ratio (E. R.) can be used as a measure of damaging force that may be imposed upon structures due to ground vibrations.
2. (a) The E. R. is proportional to the square of the weight of explosive detonated at any instant.
   (b) The E. R. decreases as the distance from the center of the explosion increases.
3. Since the E. R. is proportional to the square of the weight of explosive, at any instant, the use of delays decreases the E. R.
4. The equation $\left(\frac{50}{D}\right)^2 C^2 K = E.R.$ is a fair approximation of energy ratio to expect from a specified number of pounds of dynamite.
5. Generally, if the charge of dynamite to be used is proportioned so that the number of pounds per delay develops an E. R. in the equation of less than 3

no damage is likely to occur in structures composed of standard engineering building materials that have not been prestressed.

6. By preliminary vibration tests of the ground strata in question, it is possible to determine the ground constants and thus determine the amount of explosives that can safely and practically be used without causing damage to adjacent structures.

Objectives

We wish to determine:

1. The manner in which the transmitted energy varies with the amount of explosive detonated at any instant.
2. The manner in which the transmitted energy varies with distance from the source.
3. The total amount of energy imposed upon a structure by ground vibration that will damage the structure.
4. Whether or not it is possible to predetermine the safe amount of explosive that can be used in a specific location.

Procedure

Our basic assumption during these investigations was that the vibration in the ground was simple harmonic in nature.

Starting with the equation that K. E. $= \frac{W V^2}{2g}$ it is possible to show that this equation can be reduced to give a value in terms of acceleration, i.e.—

$$K.\ E. = \left(\frac{W}{2g4\pi^2}\right)\left(\frac{a^2}{n^2}\right)$$

The first fraction of the equation is a constant at any location depending on the mass set into vibration. Therefore, if the mass is constant, the K. E. may be considered to be proportional to $\frac{a^2}{n^2}$ hereafter termed the E. R.

Throughout this analysis most of the curves pertaining to blasting are comparisons of E. R. with distance or pounds of dynamite. This was necessary because we were not able to evaluate the mass of ground that was in motion.

In all cases, the instrument was placed upon the surface of the earth, rock, or the soil overburden.

Measurements were taken when:

(a) The explosive was detonated in the rock with the instrument located on the rock.
(b) The explosive was detonated in the rock with the instrument located on the surface of the soil overburden.
(c) The explosive was detonated in the soil below the surface with the instrument located at the surface.
(d) The explosive was detonated in the rock and/or soil with the instrument located in buildings.

Among the variables we had to deal with were: distance from the energy source; weight of explosive being used, either in the total shot or in the individual delays; variations in the density and consistency of the soil; and variation in the rock strata due to faults and dips, etc.

We endeavored to overcome these variables (1) by locating the instrument at a constant location and varying the number of pounds of dynamite or (2) by keeping the number of pounds of dynamite as constant as possible and locating the instrument at different distances from the source.

Findings

It is evident from the equation used that the E. R. is always a ratio involving acceleration and frequency. Therefore, in all cases we were interested in both these factors. The frequency of vibrations in the ground is a potent factor in the amount of energy that is transmitted to structures. This was found to be evident when we made a comparison of the vibration in rock with the vibration in earth overburden.

Frequencies

The rock, being a uniform elastic medium, transmitted the vibrations readily but always at a frequency of vibration that was relatively high. We have measured frequencies of vibration in rock as low as 40 cycles per second, and as high as 80 to 90 cycles per second. Because the E. R. is inversely proportional to the square of the frequency, the resulting energy imposed upon the structure was always small, even though in many cases the instrument was so close to the blast that accelerations greater than gravity were measured. The frequencies in rock were always so high that the resulting E. R. transferred to the structures was low.

The frequencies of vibration through the earth medium were

always found to be much lower than those through rock. For the same acceleration, the resulting E. R. imposed upon the structures built upon earth was many times greater than that imposed upon the structures founded on rock. Our experimental data have indicated that frequencies in the earth range from a low of 7 to 10 cycles per second to a high of 40 cycles per second.

It is evident that the safety of structures located in or on the overburden is the critical problem.

The frequencies of vibration in the three planes were not always the same, varying both in magnitude and in phase. Because of these variations, it did not seem advisable to try to plot the resultant E. R.'s but to record the E. R. separately in all three planes.

Earthquake

Examples of the destructive force caused by vibrations in the ground are found in the seismological data established by the Coast and Geodetic Survey. One of the most destructive earthquakes recorded in the past few years in the United States was the 1933 earthquake in Long Beach. The records as established by the Coast and Geodetic Survey show an average acceleration of approximately 3 feet per second per second, and a frequency of about one cycle per second measured in the basement of buildings. This would establish an E. R. equal to $\frac{9}{1} = 9$.

The force associated with this E. R. demolished wall bearing brick buildings, destroyed chimneys and porches on frame structures, produced damage to and in some cases collapse of the water tanks, and caused some but not excessive breakage in underground utilities.

Although the effects of a large E. R., as indicated above, are known we did not know at what lower E. R. the damage would be likely to start.

Experience to date has shown that if the E. R. is kept below 3 no damage is done to buildings of sound construction and material.

Dampening Due to Distance

Measurements were taken of the ground vibrations during the excavation of rock for a water tunnel shaft. Because this was a practical operation and not an experimental one, it was impossible to control accurately the number of pounds of dynamite used in

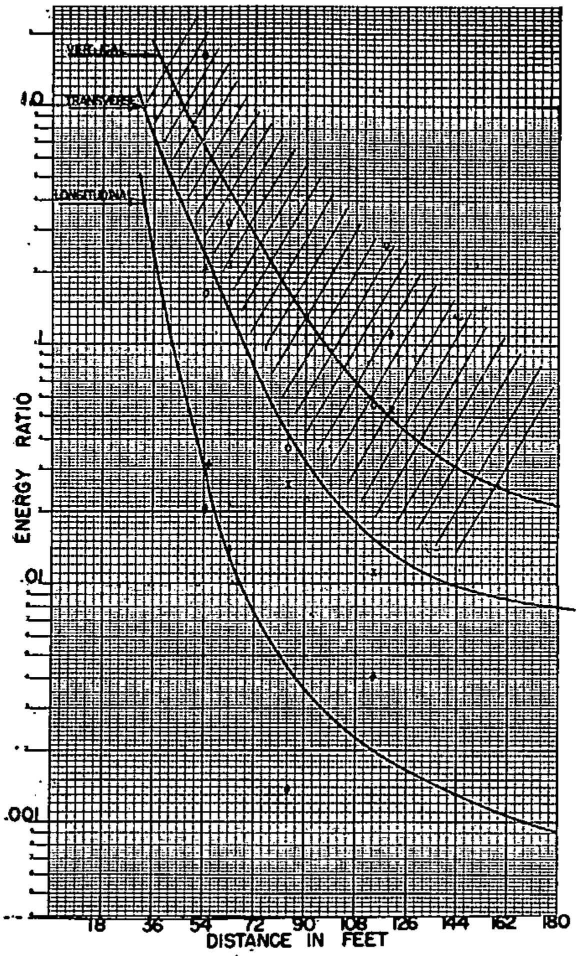


FIG. 2.—DAMPENING DUE TO DISTANCE. (Shaft Sinking)

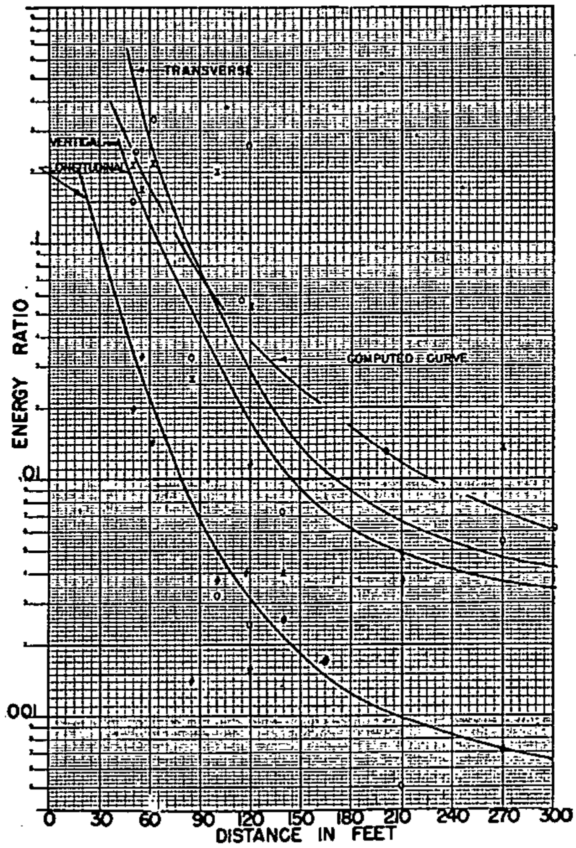


FIG. 3.—DAMPENING DUE TO DISTANCE. (Sewer Tunnel)

each delay or in each shot. Since the variation was not great, the instrument was located at varying distances from the source, and an endeavor was made to coordinate the E. R. at each distance with the number of pounds of dynamite used per delay. Figure 2 is a plot of the vibration measured in the vertical, longitudinal, and transverse planes as the instrument position varied from approximately 50 feet to 125 feet from the source of vibration.

The material being excavated was a very hard rock and had an overburden averaging approximately 20 feet of clay and silt. The instrument in all tests was located on the surface of the overburden. Figure 2 shows the dampening effect at various distances from the source of the vibration.

Because of the tremendous variation in the location of the points on the graph, the curves at best can be taken only as averages. Most

of this scatter was caused by the fact that it was impossible to have exactly the same number of pounds of dynamite in each individual delay.

Further tests taken on the same shaft sinking job showed that as the depth increased the dampening effect continued with distance. The distance increased up to approximately 270 feet from the source of vibration. After approximately 200 feet from the source, the dampening with distance tapered off and was not so rapid.

As in Figure 2, the curves on Figure 3 can be used as general indications of the dampening that occurred with distance.

As will be noted in this graph, an attempt was made to establish a relation between the number of pounds of dynamite in the vibration source and the E. R. At approximately 50 feet from the source of vibration the equation reads as follows: $C^2\,(0.001) = \text{E. R.}$ We established empirically the following equation for distance:

$$\left(\frac{50}{\text{Distance}}\right)^2 C^2\,(0.001) = \text{E. R.}$$

The curves in Figure 3 can be used as a general indication of the dampening that occurs with distance but should be considered only general because of the variation of the points on the curve. The variation of these points were again primarily caused by the fact that we were unable to standardize the number of pounds of dynamite used per delay.

Delays

In all cases, the establishment and use of delays materially decreased the total vibration. Each individual delay was characteristically recorded on the film, and at no time was there an overlapping or continuous vibration between delays when the delays acted as they were designed. Whenever two or more delays went off at once, we obtained a cumulative effect of the vibration equal to the square of the number of pounds of dynamite in those delays.

The equations shown were established for instantaneous shot, and therefore the C^2 in the equation is the square of the number of pounds of dynamite used in each delay.

Dampening Due to Reduction in Charge of Explosive

Further tests were made in the excavation of tunnel work in which a very stiff clay had to be excavated. In order to operate

economically, the contractor drilled and shot this clay similar to the operation performed in blasting rock.

In all the measurements taken at this time, the direct transmission of the vibration through the clay were measured.

In determining the effect in the clay caused by the variation in pounds of explosive, the instrument at all times was located at a distance of 50 feet horizontal from the source of vibration. The overburden above the excavation in all cases was approximately 20 feet, but the total depth of overburden was approximately 90 feet. Figure 4 is a plot of E. R. in relation to the pounds of explosives per delay.

Again it was found that vibrations from all shots were separated, that the vibrations were not cumulative. Therefore the number of pounds of explosive in each delay was proportional to the amount of vibration produced. A variation will be noted on the chart, but in general the curves indicate an increased amplitude of vibration with an increased number of pounds per delay.

In this case, since the energy source was in the clay and the measurements were taken in the same medium, the transverse vibration appeared at all times to be the maximum.

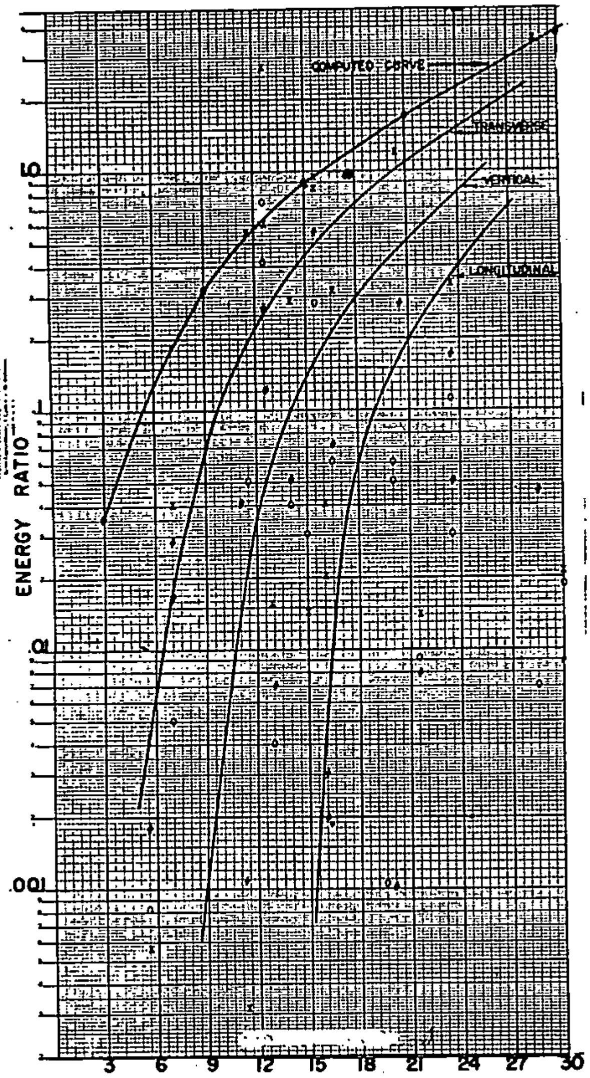
An investigation of the curve in the transverse plane shown in Figure 4 allows us to establish the equation that $C^2 (0.004) = E. R.$

Damage

During this operation, an endeavor was made to control the vibration by limiting the charges per delay. The maximum charge recommended in this case was 32 pounds of explosive per delay, which by calculation should produce an E. R. of three. Experience throughout this area, which is almost completely built up with residential homes, schools, and churches, indicated that when the structure had not been pre-stressed and the materials of construction were average, no damage occurred.

However, where there were structures that had been pre-stressed because of settlement or movement of any sort, and some showed actual breaks, an E. R. of three had sufficient force to increase the width of the cracks in some of the foundation walls.

As can be expected, the number of charges per shot could not always be controlled because at some times, either because of the inaccuracy of the delays or because of the propagation of one delay



Pounds of Dynamite

FIG. 4.—DAMPENING DUE TO REDUCTION IN CHARGE OF EXPLOSIVE.

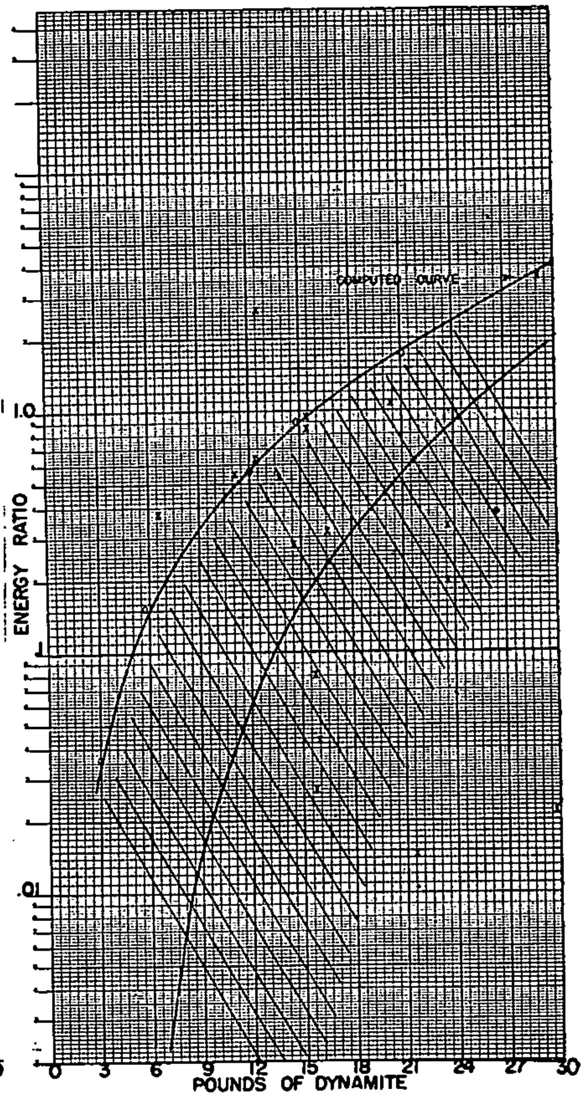


FIG. 5.—DAMPENING DUE TO REDUCTION IN CHARGE OF EXPLOSIVE.
(Transverse plane)

to another due to impact, there was more than one delay going off at once. When this occurred, the force of vibration increased with the square of the number of pounds of dynamite exploded at any given instant. In one case, a sufficient number of delays went off at once to explode approximately 70 pounds of dynamite. This produced an E. R. of approximately 10, and actually canned goods were knocked off the shelves of a grocery store within 75 to 100 feet of the shot.

Damage was done to a building that was constructed as a wall bearing structure and that had a terra cotta face built against the brick. This terra cotta face at certain locations was knocked off, but

it was found upon examination that there were no ties between the terra cotta and the brickwork. This would not be considered good average building construction. However, this facing only came off when the E. R. was greater than three.

By separately plotting the longitudinal, transverse, and vertical planes, a better picture was obtained of the scattering of the points plotted, Figures 5, 6, and 7. The cross-hatched area of these charts can be called the Scatter Zone.

A study of the transverse plane data shows that with 16 to 17 pounds of explosive the measured E. R. varies from 0.02 to 0.9. However, this is still less than the threshold limit of 3.

Available tests using the equation:

$$\left(\frac{50}{D}\right)^2 C^2 (K) = E.\,R. = 3$$

allow a sufficient charge of explosive to effectively break the material being excavated. In fact, generally efficient and practicable charges of explosives have produced E. R.'s less than 3.

Frequencies in Separate Planes

The frequencies of vibration through the ground were found to be different in each individual plane.

Figure 8 is a magnified photograph of an instantaneous shot showing a comparison of the frequencies in each of the longitudinal, vertical, and transverse planes.

In order to give a better evaluation of the shape and frequency of the wave, the record on all three planes has been traced off separately. The first tracing is that of the record in the longitudinal plane or compression wave. This may also be called the push-pull wave.

This record is typical of the type of wave found in the longitudinal plane, and it will be noted that low frequencies predominate.

The second tracing is that of a typical record in the vertical plane. In this record, you will note that as the vibration comes into existence, there are large amplitudes, and the slope of the line indicates high frequencies. In all cases, high frequencies predominated in the vertical plane.

Although it can be seen that there are low frequencies and small amplitudes at the end of the wave, this is primarily caused by the dampening effect in the earth and does not indicate the maximum amount of energy in this plane.

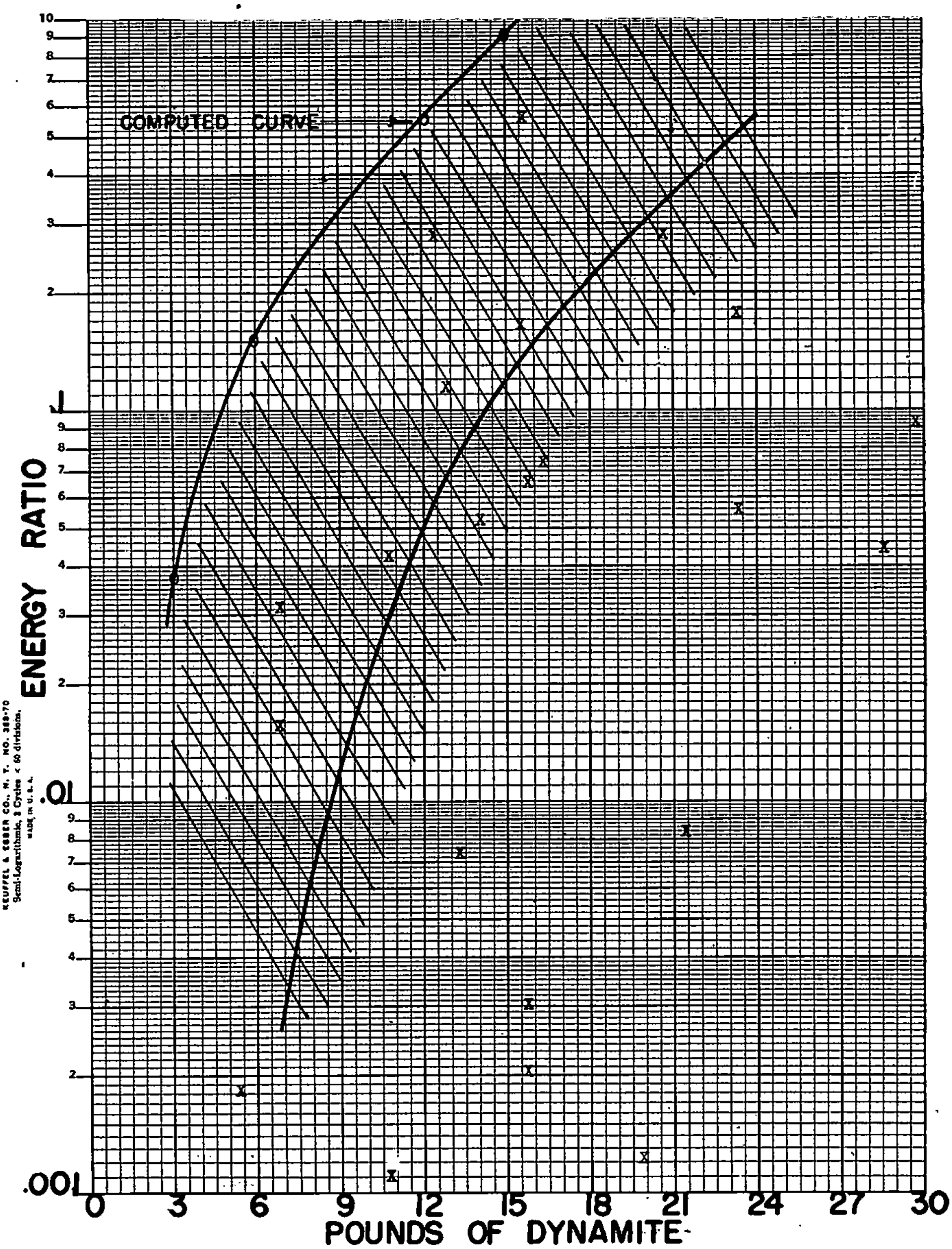


FIG. 6.—DAMPENING DUE TO REDUCTION IN CHARGE OF EXPLOSIVE.
(Longitudinal plane)

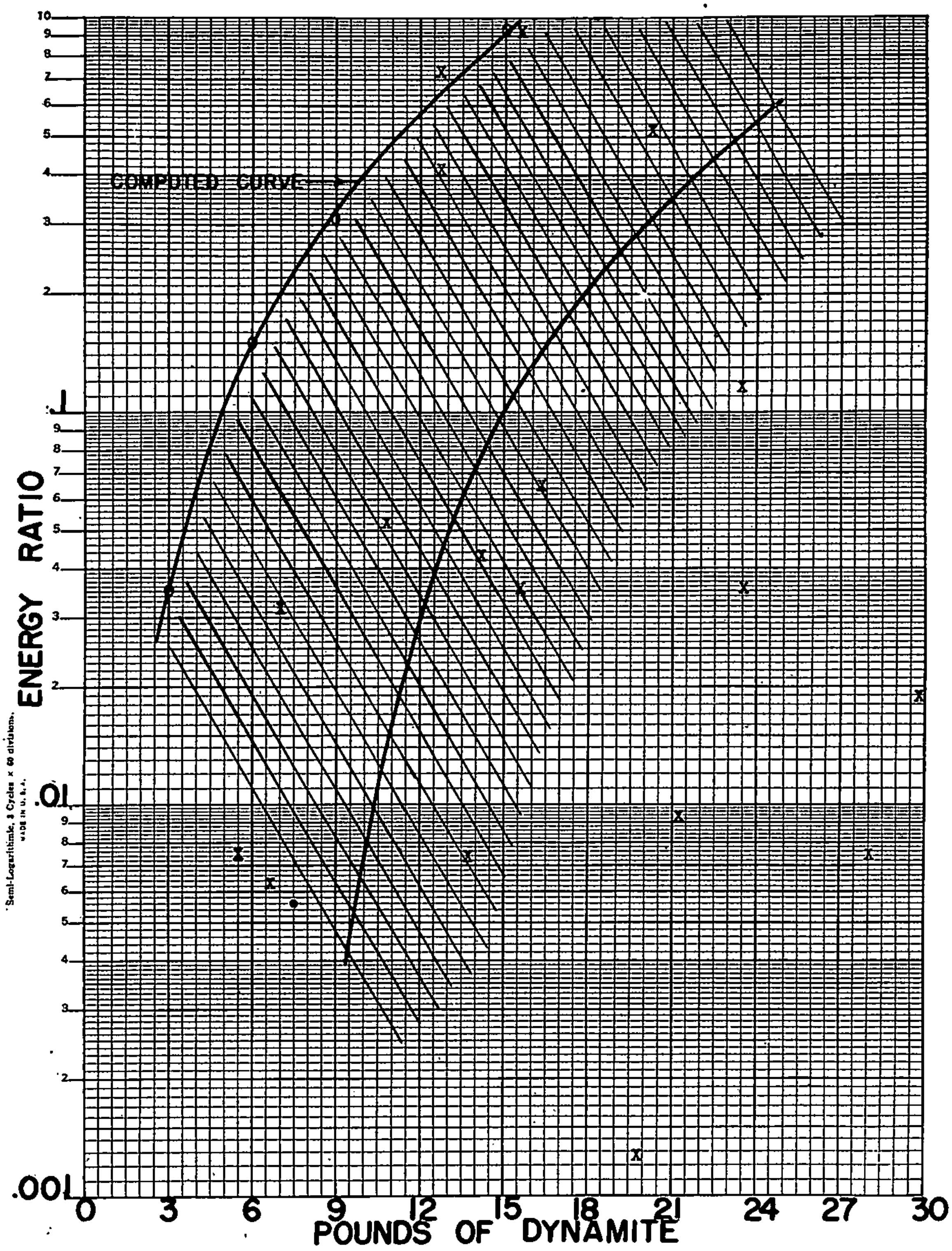


FIG. 7.—DAMPENING DUE TO REDUCTION IN CHARGE OF EXPLOSIVE.
(Vertical plane)

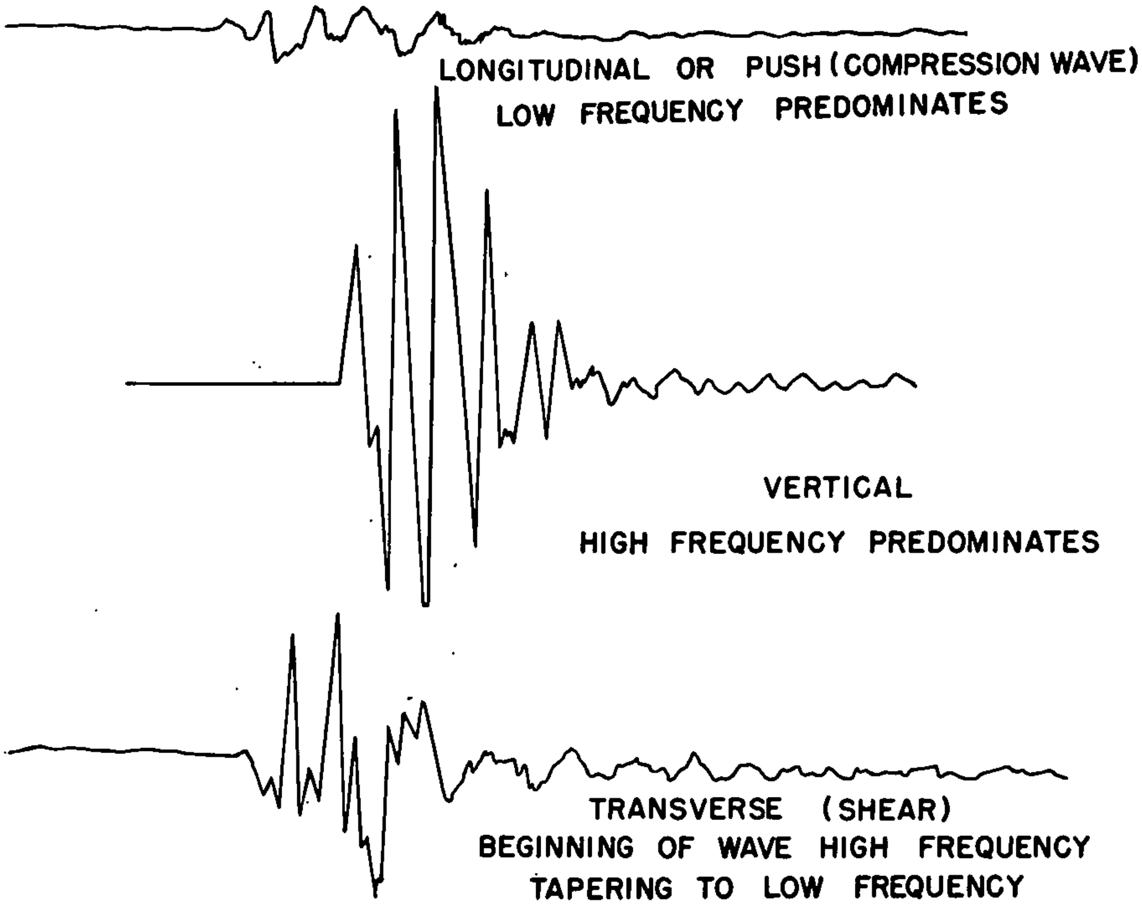


FIG. 8.—COMPARISON OF FREQUENCIES.

The final tracing of the original record is in the transverse plane, which can be called the "shear" wave in the earth.

At the beginning of the vibration, as it is first picked up by the instrument, the high frequencies definitely predominate, but they are rapidly wiped out by the low frequencies which give us the maximum energy in this plane.

Because the vibrations in all three planes are not in phase, and the frequencies in each plane differ, a very complicated movement of the ground due to the vibrations set up by the blast is indicated. No doubt each individual vibration from any instantaneous shot contains what might be called a spectrum of frequency, the high frequencies being predominant at the beginning of the vibrations in both the vertical and transverse planes, and the low frequencies in the longitudinal plane.

In measuring the record, the maximum combination of high amplitude and low frequency was always determined because this gave the highest E. R. The maximum E. R. was obtained in the

transverse plane a short time after the vibration started in this plane. The high frequency vibration was overcome by the more forceful low frequency ones.

The maximum combination of amplitude and frequency was measured in each separate plane, even though they did not come at the same instant. This procedure gives a maximum E. R. in each plane. The vector sum of these maximum E. R.'s would give a resultant greater than expected. However, this resultant would be definitely on the safe side.

Energy Ratio

Because of our previous assumption that the mass of earth in vibration was unknown and that therefore in like locations the mass was the same, we made the basic assumption that E. R. $= \frac{a^2}{n^2}$.

Our investigation and test has shown that when the E. R. in the ground becomes three or more, old pre-stressed structures are likely to be damaged. Further, when the E. R. in the ground becomes six, damage will occur to residential types of buildings or brick wall bearing structures.

Because the E. R. is made up of the square of the acceleration divided by the square of the frequency, it is readily seen that if the frequency is high, the acceleration can also be high and still be within a safe range.

A visual indication of this ratio of acceleration and frequency is shown in Figure 9. A study of this chart indicates that when the frequency of vibration in the earth strata is approximately 2, an acceleration of 3½ feet per second per second will reach the damage threshold and one of 4.8 feet per second per second is likely to cause damage. On the other hand, if the frequency within the earth strata itself is 15, an acceleration of 24 feet per second per second would have to be induced in order to reach the threshold limit.

Thus, in a stiff clay medium, whose frequency may be in the vicinity of 20 cycles per second, a relatively large acceleration will not bring us into the damage zone. On the other hand, if there is a sedimentary deposit completely saturated with water, the frequency will be low, probably in the vicinity of 5 to 7 cycles per second, and the damage range of the structure will be reached very quickly.

Because the E. R. varies inversely with the square of the fre-

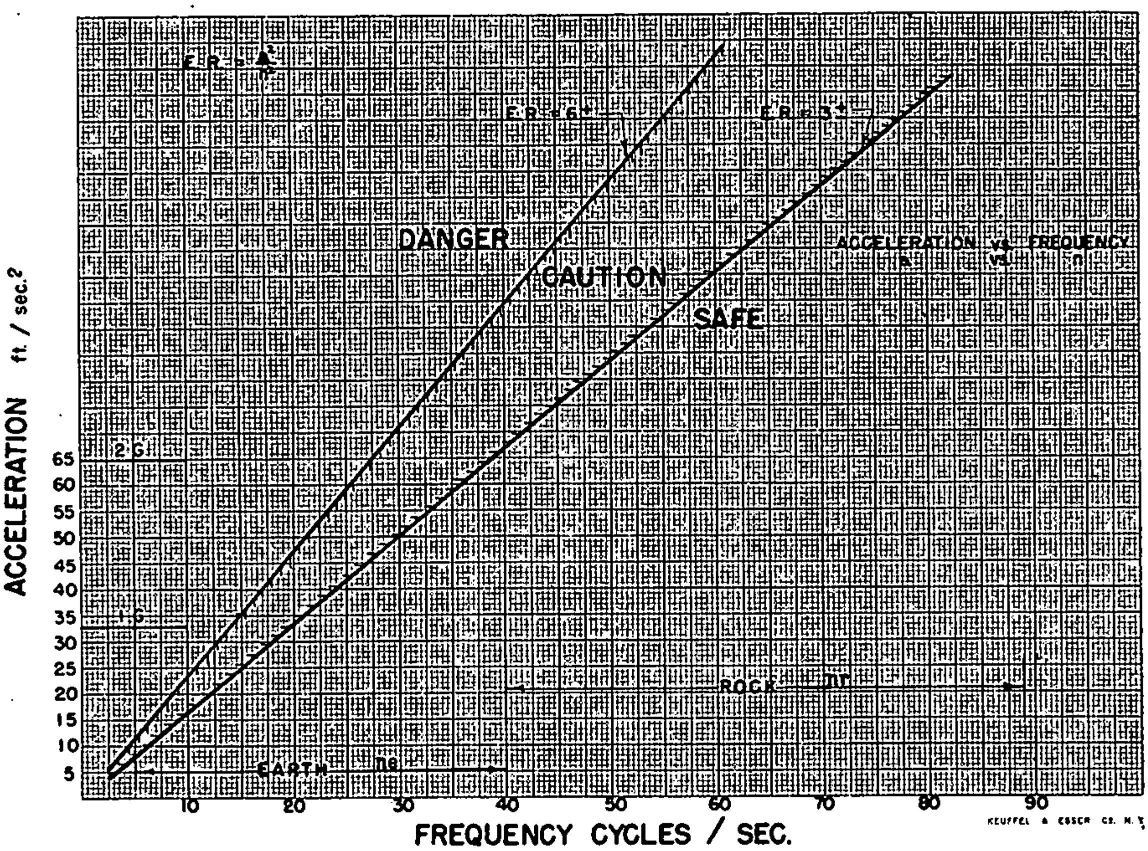


FIG. 9.—ENERGY RATIO LIMIT CHART.

quency and the constant in the equation $C^2 K = E. R.$ only fluctuates from approximately 0.001 to 0.004 in our findings, it appears safe to say that as the frequency of the strata increases, more pounds of dynamite can be used per instant or per delay and still stay within the safe range.

The ground constant K can readily be found in preliminary tests and the average frequency of the strata involved can be indicated as well. By use of the Energy Ratio Chart at a 50 foot distance, the number of pounds of dynamite allowable to keep within the safe range as shown by the lower threshold mark on the Energy Ratio Chart can be found with relative ease.

As our research has shown, for the distances involved, i.e. 50 to 250 feet the E. R. decreases inversely with the distance. Therefore by inserting the distance D in the equation the fluctuation in pounds allowable as distance increases can be determined with relative ease.

It is interesting to note that as the frequency of the strata decreases, the range between the lower threshold limit and actual danger

points becomes very small. The lowest frequencies that we have been able to measure were in swampy ground that had a frequency of 7 cycles per second. The earthquake frequencies as measured by the Coast and Geodetic Survey instruments show frequencies as low as 1 to 3 cycles per second. At these frequencies, even 10 per cent of gravity brings the E. R. into the damage zone.

By the same token, as frequencies such as those found in the rock strata increase, accelerations equal to 1-g or even 2-g can be obtained without exceeding the safe E. R. limit.

Displacement vs. Frequency

Ground energy ratio can be used with displacement and frequency measurements as well as acceleration frequency measurements. The Kinetic Energy equation can be set up in relation to displacement and frequency as well as acceleration and frequency as follows:

$$\text{K.E.} = \frac{W V^2}{2g} = \frac{W}{2g4\pi^2}\frac{a^2}{n^2} = \frac{W}{2g4\pi^2}16\pi^4n^2D_1^2$$

or

$$\frac{a^2}{n^2} = 16\pi^4n^2D_1^2$$

Because $\frac{a^2}{n^2}$ is designated as Energy Ratio, in regard to acceleration then $16\pi^4n^2D_1^2$ can be designated as Energy Ratio in regard to displacement.

$$\text{E. R.} = 16\pi^4n^2D_1^2$$

Taking lower threshold as 3

$$\text{Then E. R.} = 3 = 16\pi^4n^2D_1^2$$

$$\text{or } D_1 = \frac{.0439}{n}$$

Taking upper threshold as 6

$$\text{Then E. R.} = 6 = 16\pi^4n^2D_1^2$$

$$\text{or } D_1 = \frac{.0621}{n}$$

By use of a displacement instrument similar to the Leet Portable Seismograph ground measurements can be taken to determine the

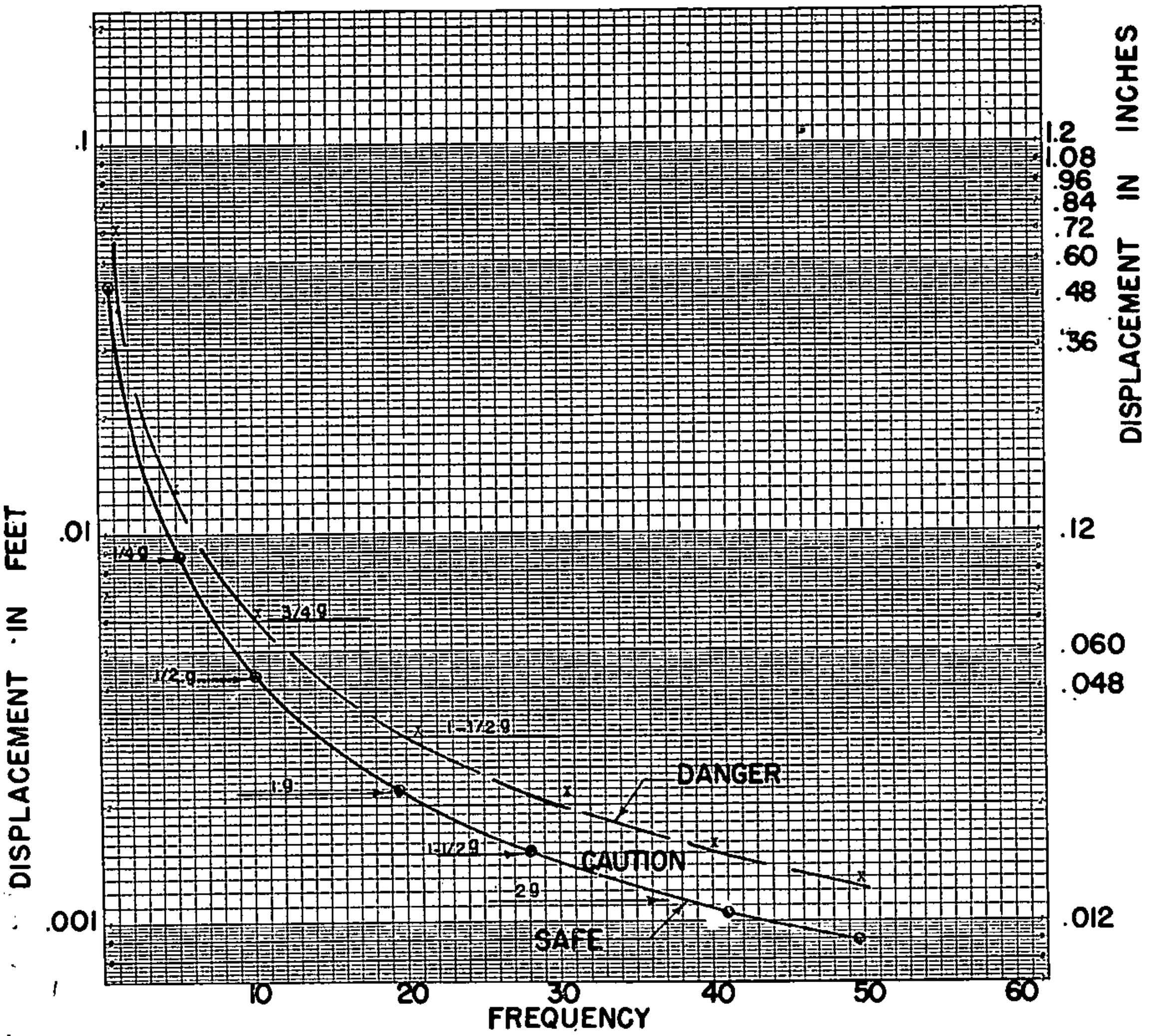


FIG. 10.—ENERGY RATIO LIMIT CHART, DISPLACEMENT VS. FREQUENCY.

amount of vibration transmitted in relation to the weight of dynamite used in the detonation. Figure 10 indicates the safe range and the danger range of ground vibration for an energy ratio of 3 as the lower threshold limit and an energy ratio of 6 as the upper threshold limit. The equation for the number of pounds of dynamite allowable in any instant will be the same or $\left(\frac{50}{D}\right)^2 C^2 K$ will be the same except for the right-hand side of the equation. The fraction $\frac{a^2}{n^2}$ would change to $16\pi^4 n^2 D_1^2$. Therefore the equation in using displacement and frequency measurements will be asfollows:

$$\left(\frac{50}{D}\right)^2 C^2 K = 16\pi^4 n^2 D_1^2$$

In this equation D_1 is equal to the ground displacement and n is equal to the frequency of the ground vibration.

With control tests and equating the right-hand side of the equation = 3 as the lower limit, knowing the number of pounds of dynamite used in the control tests, K can be found, thus allowing one to determine the safe number of pounds of dynamite that can be used per delay, determined from displacement and frequency measurements of the ground.

Owners' Reaction to Vibration

The limits of ground vibration needed to cause damage to structures having been determined by these experiments, the question arises as to the Level of Human response to vibration. Physiological tests have established the lower limit of human response to vibration to be 1/100 of the vibration that causes damage to ordinary structures.

Our experiments showed that it is possible to predetermine the amount of explosive that can safely be used in any blast without injuring the adjacent structure, but claims as to damage were still being made by the owners. Investigation of these claims showed that no structural damage had occurred. From this we can conclude that because the vibration was felt by the people living in the homes adjacent to the blasting, that they assumed damage occurred. This in all probability is because of the ability of people to feel vibration long before any structural damage could occur.

A very thorough study of human response to vibrations was made by Reiher and Meister at the Technical University of Stuttgard in Germany about 1931.

This experiment was performed by vibrating a freely suspended platform, 6′×4′, by means of an unbalanced electric motor between 3 to 70 cycles per second and .00004″ amplitude.

The results are shown in Figure 11 in accelerations and in Figure 12 in displacements in inches vs. frequency.

When the subjects were standing, they were much more sensitive to vertical than horizontal vibrations. When lying down the vertical vibrations were not as noticeable as the horizontal and the motion perpendicular to the long axis of the body in the horizontal plane were most disturbing.

All subjects easily noticed the vibrations at a level 1/100 of that which was the caution range for structures. In addition, severe vibra-

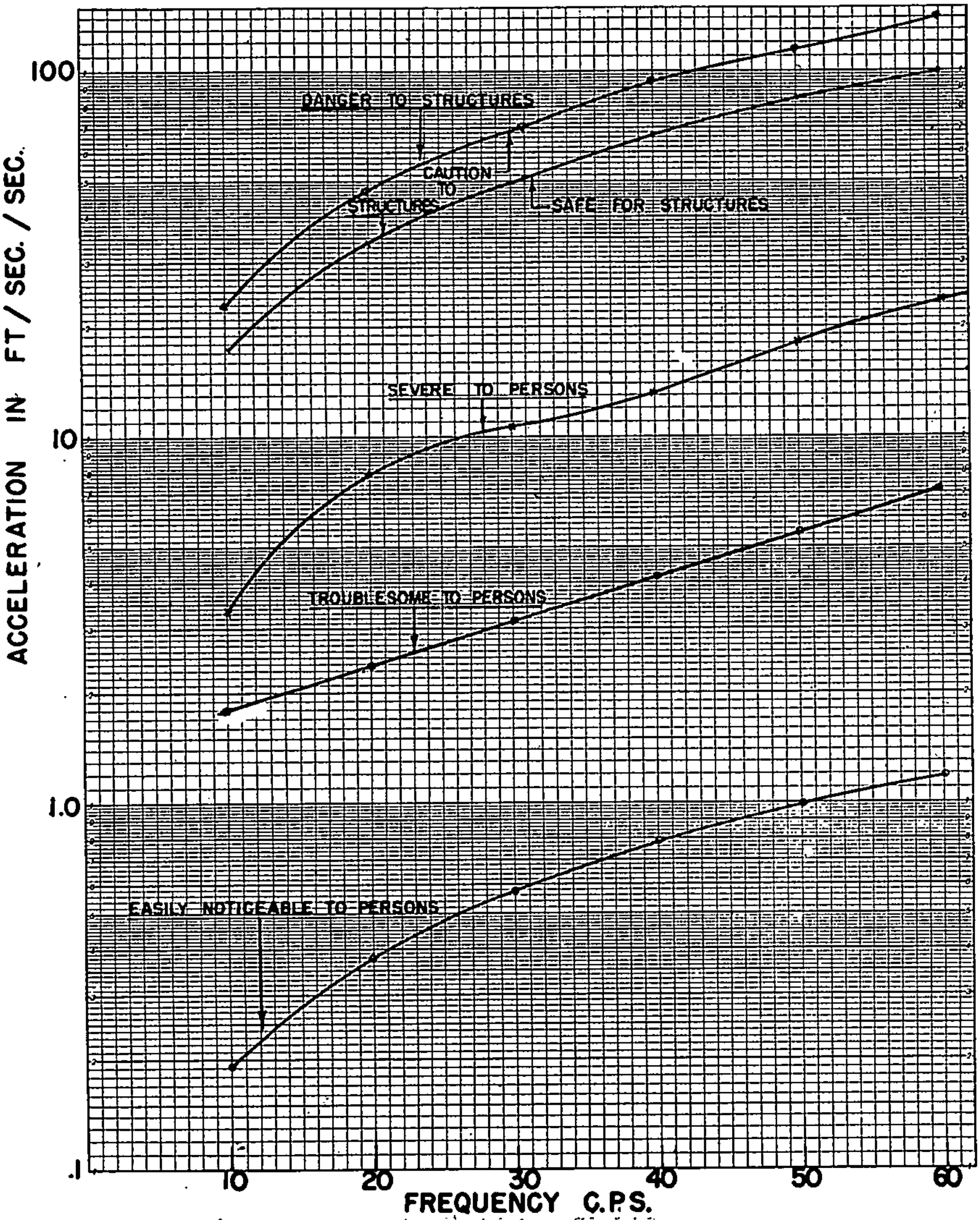


FIG. 11.—LEVEL OF HUMAN RESPONSE TO VIBRATION.

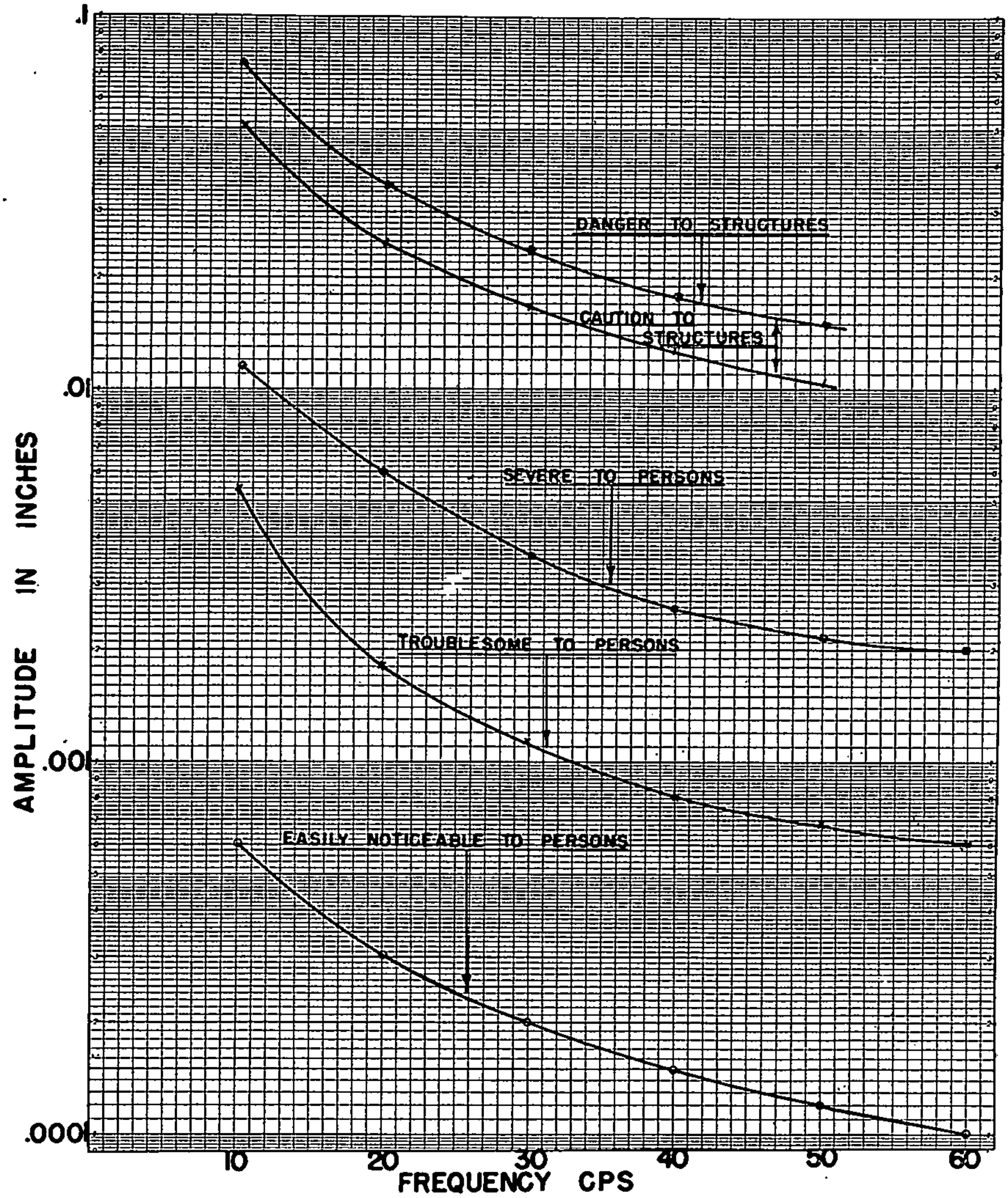


FIG. 12.—LEVEL OF HUMAN RESPONSE TO VIBRATION.

tions to persons, which comes about 1/5 of that needed to damage structures, would be very startling to a house owner, although it would not cause damage to his structures.

Figure 12 plotting amplitudes vs. frequency shows that at 20 cycles per second, a displacement of no more than the thickness of a piece of paper is easily felt by persons and a vibration of only 1/64" would be a severe vibration to persons.

The noise accompanying a blast and the fact that persons feel very small vibrations lead many owners to assume that the vibration is enough to injure their structure based upon their own response to the movement.

It might be advisable for the contractor performing the operation to warn the property owners as to the time of each blast, thus eliminating the element of surprise that comes from the noise and vibration.

At the same time informing the owners that tests have been made to determine the ground constants so that the explosives are limited to insure no damage to ordinary structures will more likely obtain better owner cooperation.

General Summary

1. It is practical to use the measured ground accelerations and frequencies to indicate the ratio of energy being transmitted through the ground.

2. An investigation of over 1,000 residential homes, stores of 2 stories high, some schools, churches, and hospitals that were investigated before the disturbance or vibration occurred and after the vibration occurred, shows that if the energy ratio as measured by acceleration and frequency is kept below 3 there will not be damage to buildings of average workmanship and good materials.

3. A study of the records shows that the energy ratio is proportionate to the amount of explosives detonated at any instant. Therefore the use of delays in any general shot allows a control of the amount of energy ratio transmitted through the ground.

4. A study of the wave train records shows that the instantaneous shot invariably produced a greater energy ratio in proportion to the pounds used, than any other delay. Bureau of Mines averaged this instantaneous wave to be 11 times the following waves due to delays.

5. Equation $\left(\frac{50}{D}\right)^2 C^2 K = E. R.$ is practical in predetermining

the amount of vibration for energy ratios that will be transmitted through the ground.

It is only necessary to measure the transmission and determine K by use of known amounts of dynamite, determine the distance of the nearest structures to be able to determine the number of pounds of dynamite that safely can be used, without injury to the structures.

6. When using ordinary delays, the wave trains from each separate delay invariably died out before the next delay was detonated.

7. At no time did we find the wave trains overlapping from one delay to the next.

8. The range of this investigation covered the distance from 25 to 250 ft. and charges of explosives from one pound to one-hundred pounds. It is conceivable that for greater distance and greater poundage, this equation may not hold wholly true.

9. Displacement and frequency can be used as well as acceleration and frequency in determining E. R. as shown in Chart 2.

10. Experimentation shows that people are very sensitive to vibration, and the lower level of human response to vibration, which is easily felt by all persons, is 1/100 of the vibration that approaches the caution range for structures.

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Abbreviations

a = Acceleration in feet per second.
n = Frequency of vibration in cycles per second.
K.E. = Kinetic Energy in foot pounds.
E.R. = Energy Ratio = $\frac{a^2}{n^2}$.
W = Weight in pounds.
g = Acceleration of gravity in feet per second per second.
K = Constant (depending upon local ground conditions).
C = Pounds of explosive detonated at any instant.
D = Distance from the center of detonation in feet.
D_1 = Ground displacement.